PA38

Formation of duct in Plasma by High Power Microwave and Self-Focusing

H. ITO, Y. NISHIDA, and N. YUGAMI
Department of Electrical and Electronic Engineering,
Utsunomiya University,
2753 Ishii-machi, Utsunomiya, Tochigi 321, Japan.

Abstract

The first experimental demonstration of ducitng of high power microwave in a preformed density channel is studied. The microwave remains trapped and guided in a preformed density channel. These results are in good agreement with a numerical model describing the microwave propagation.

1. Introduction

One of the most interesting topics is the application of the laser to plasma based particle accelerators with a ultrahigh gradient. A number of ways to excite plasma waves having gradients as high as several ten of GeV/m have been proposed so far. A laser driven accelerator that has a number of attractive features is the laser wakefild accelerator (LWFA) [1,2]. But LWFA has the fault that the acceleration distance is severely limited to the diffraction length, or Reyleigh Length $z_R = \pi r_0^2/\lambda_0$, where λ_0 is the laser wavelength and r_0 is the laser spot size at focus. The self-guiding [2] of an intese electromagnetic wave in a plasma has been proposed to overcome its limitation. This phenomenon is particularly interesting for processes requiring a long interaction length such as x-ray lasers [3] and laser-driven accelerators. More recently numerous theoretical works on this subject [4,5] have been performed and experimental results [6,7] have also been presented.

2. Theory of optical guiding

One approach to the guiding of an intense electromagnetic waves uses the effect depending on self-induced modulations of the plasma refractive index. In a plasma there are two types of optical guiding mechanisms. One is the self optical guiding due to the ponderomotive force of an intense electromagnetic wave and the other is the optical guiding due to the relativistic effect. The former utilizes the dependence of refractive index on the plasma, which is given by

$$N = \sqrt{1 - (\omega_p/\omega_0)^2}, \qquad (1)$$

where ω_0 is the incident-wave frequency, $\omega_p = (4\pi n_e|e|^2/m_e)^{1/2}$ is the plasma frequency and n_e is the electron density. With the preformed density channel along the pass of electromagnetic wave, it propagates in this channel over distances exceeding Reyleigh length. The latter results from the increase of the refractive index due to the relativistic quiver motion of electrons. Because the refractive index has the largest peak on the axis where the intensity of electoromagnetic wave has a maximum, the distribution of refractive index is the same as that of an optical fiber. Such relativistic self-guiding occurs when the inident-wave power P exceeds a critical power [8,9] given by $P_c = 16.2(\omega/\omega_p)^2$ GW.

3. Experimental Set up

The experimental arrangement used in the present studies is shown in Fig.1. A cylindrical, unmagnetized argon plasma is produced in a stainless-steel chamber of 60 cm length by 32 cm diameter covered with a number of multidipole permanent magnets for a plasma confinement.

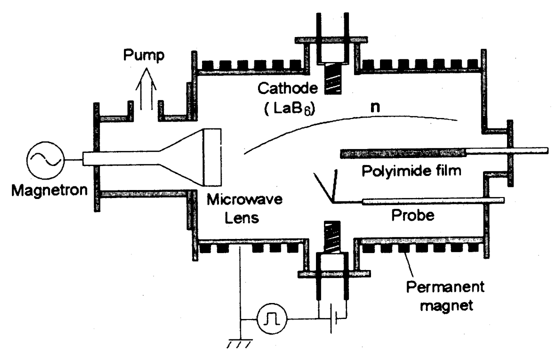

Fig.1 Experimental apparatus

The plasma is produced by a pulsed discharge with discharge duration of 2 msec and 10 Hz repetition between the LaB_6 cathode and the chamber wall. The plasma density is measured by both a cylindrical and a plane Langmuir probe. The typical plasma parameters are the maximum electron density $n_0 \approx 2.0\times10^{12}$ cm^{-3}, electron temperature $T_e \approx 3 \sim 5$ eV in an argon gas pressure $P_0 = 3 \sim 4 \times 10^{-4}$ Torr.

The pulsed microwave with frequency $f_0 = \omega_0/2\pi = 9$ GHz and a maximum power of 250 kW and the pulse duration of 1 μsec in FWHM is irradiated from a rectangular horn antenna (aperture area= 13.5×10.5 cm^2) with a metal lens located at a lower end of plasma density toward a higher density area along the chamber axis.

4. Experimental Results

The density channel is formed by inserting the Polyimide film sheet with 240 mm length by 15 mm width and 125 μm thickness at the center of the chamber filled with the plasma. In the present experiment, the sheet is inserted from the higher density to 15 cm position from the edge of metal lens. We may estimate that the radius of density channel is about 1 cm.

When the microwave pulse is injected into this density channel, Fig.2 shows an axial profile of observed electric field pattern as a function of incident power. We observe that with increasing the incident microwave's power the microwave pulse propagates deeper along the density channel and that the electric field also becomes stronger. The electric field tends to be confined around the axis ($r = 0$ cm) as the microwave pulse propagates along the channel. We can measure that the spatial separation of three peaks (α, β, γ) appear in Fig.2 (a) is about 2.2 cm. Three peaks can be visible as the incident power increases. We know that the wave length of the fundamental TE mode in the wave guide (WRJ-10: 2.29×1.02 cm^2) is $\lambda_g = 4.8$ cm. If we assume that the observed wave in the experiment is the fundamental TE mode, we suppose that the stanting wave of the mode is formed in a density channel.

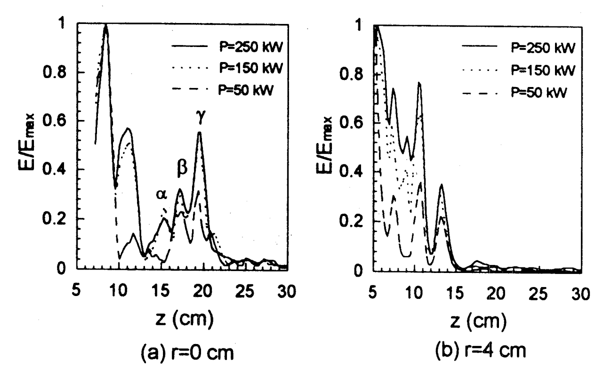

Fig.2 Profiles of the nomalized field E as a function of the axial distance. Radial positions (a) $r = 0$ cm, (b) $r = 4$ cm.

Figure.3 (a) shows the half width of the radial field profile Δr as a function of z. The half width Δr changes along the channel and has minimum around $z = 19 \sim 20$ cm, while the field amplitude has maximam on the axis. Therefor, we can say that the microwave pulse is focused at $z = 19 \sim 20$ cm.

Figure.3 (b) shows the half width of the field radial profile as a function of the incident power. Fig.3 (b) indicates that the half width has a minimum at the maximum power $P = 250$ kW. It is evident from Fig.3 (b) that the half width tends to decrease with increasing the incident power.

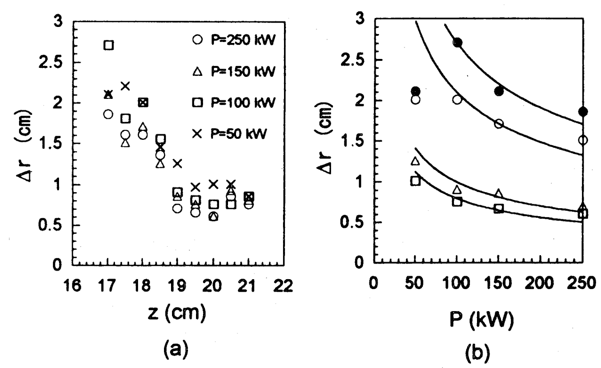

Fig.3 (a) Half width of radial field profile Δr as a function of the axial distance (z). (b) Half width Δr as a function of the incident power. Solid circles, open circles, triangles, and squares are the axial positions $z = 17$ cm, $z = 18$ cm, $z = 19$ cm, and $z = 20$ cm, respectively. Solid lines represent theorical calculations.

5. Discussion

In order to interpret the observed behavior, we calculate a transverse profile of the microwave in the density channel. We assume that the microwave pulse is weak enough to neglect the relativistic effect. We use a propagation model approximated by that in an opticl fiber with refractive index N_1 inside and N_2 outside. Because the microwave field is axially symmetric, we can look for the fundamental TE mode solution of Maxwell's equations. In a slab geometry, this solution [10] is given by

$$E_x = \begin{cases} E_0 \cos(k_y y)\exp(-jkz) \ (|y| \le a), \\ E_0 \cos(k_y a) \\ \times \exp[-p(|y|-a)]\exp(-jkz) \ (|y| > a), \end{cases} \tag{2}$$

where $k_y^2 = N_1^2 k_0^2 - k^2$, $p^2 = k^2 - N_2^2 k_0^2$ and $k_0 = \omega_0/c$, c is the speed of light and a is the channel radius. Applying the continuity condition of magnetic field H_y, we obtain the characteristic equations

$$\begin{aligned} p &= k_y \tan(k_y a), \\ p^2 + k_y^2 &= k_0^2(N_1^2 - N_2^2). \end{aligned} \tag{3}$$

This numerical caluculation enables us to determine the transverse profile for propagation of microwave in the plasma channel.

We assume that the channel radius is $a = 1$ cm from the experimental result. Because the plasma density of channel outside is overdense, we may put

$N_2 = 0$. We carry out the calculation as a function of the refractive index N_1. Figure.4 shows the transverse profile of the microwave calculated for abovementioned conditions and the observed experimental results. Note that experimental and numerical values are normalized. Solid lines and dashed lines are results calculated for the cases of $N_1 = 1$ (in vacumm) and $N_1 = 0.5$, respectively. One can see that there is a fairly good agreement between experimental and numerical results. The experimental result at the lower density (Fig.4 (a)) is more agreement with the numerical result of $N_1 = 0.5$ than that of $N_1 = 1$, while at the higher density (Fig.4 (b)) the observation shows better agreement with $N_1 = 1$. These results obtained for Fig.4 can understand as follows. As the microwave propagates along the plasma channel, the electric field of microwave in the channel is maximum around $z = 19$ cm. Therefor, the refractive index of channel increases, since electrons in the channel are pushed out of the channel by the enhanced ponderomotive force. As a result, the refractive index of channel changes gradually along the plasma channel. We can say the results indicate that the ducting of the microwave is formed and that the microwave propagates along the channel.

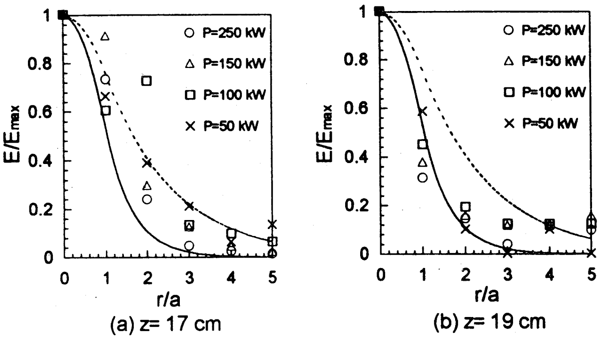

Fig.4 Normalized radial field profiles. Each curve represents numerical results. The parameters are channel radius $a = 1$, refractive index $N_2 = 0$, and $N_1 = 0.5$ (dashed line), $N_1 = 1$ (solid line). Axial positions (a) $z = 17$ cm, (b) $z = 19$ cm.

The variation of refractive index is very important and the motion of the electron has to be taken into account. The plasma is modeled using no relativistic cold fluid equations. Using the momentum and continuity equations, we can estimate that $\delta n/n_c$ is directly proportional to the incident power. The half width has $\Delta r \simeq 1/k_y$. Using equation (3), the half width is approximated by $\Delta r \simeq 1/k_y \sim 1/N_1$. Because the channel refractive index is given by $N_1 = (1 - n/n_c)^{1/2} \sim \sqrt{P}$, where we put $n = n_c - \delta n$, the half width is given by

$$\Delta r \sim 1/N_1 \sim 1/\sqrt{P}. \tag{4}$$

On writing in this result on Fig.3 (b) by solid lines, the experimental and the theorical results are in good agreement. But this comparison can only be qualitative.

6. Conculsion

We have demonstrated that the ducting of the microwave is formed and the microwave pulse remains trapped and guided in the plasma channel at the fundamental TE mode. The comparisons of the experimental observations with the theorical calculations produce good agreement for both the transverse profile of the electric field and the dependence on the incident power of the half width Δr. We have shown that the experimental result can be explained by the concept on the "otical guiding ".

Acknowledgement

We would like thank Mr. X. Xu for his corporation on establishing the experimental device. This work was supported by a Grant-in-Aid for Scientific Research from Ministry of Education, Science and Calture, Japan.

References

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[2] P. Sprangle, E. Esarey, A. Ting, and G. Joyce, Appl. Phys. Lett. **53**, 2146 (1988).
[3] N. H. Burnett and P. B. Corkum, J. Opt. Soc. Am. B **6**, 1195 (1989); P. Amendt, D. C. Eder, and S. C. Wilks, Phys. Rev. Lett. **66**, 2589 (1991).
[4] P. Sprangle, E. Esarey, J. Krall, and G. Joyce, Phys. Rev. Lett. **69**, 2200 (1992); E. Esarey, P. Sprangle, J. Krall, A. Ting, and G. Joyce, Phys. Fluids B **5**, 2690 (1993).
[5] T. M. Antonsen, Jr., and P. Mora, Phys. Fluids B **5**, 1440 (1993); Phys. Rev. Lett. **74**, 4440 (1995).
[6] C. G. Durfee III, and H. M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993).
[7] P. Monot *et al*, Phys. Rev. Lett. **74**, 2953 (1995); P. E. Young, M. E. Foord *et al*, Phys. Rev. Lett. **75**, 1082 (1995).
[8] G. Schmidt and W. Horton, Comments Plasma Phys. Controlled Fusion **9**, 85 (1985).
[9] G. Z. Sun, E. Ott, Y. C. Lee, and P. Guzdar, Phys. Fluids **20**, 526 (1987); P. Sprangle, C. M. Tang, and E. Esarey, IEEE Trans. Plasma Sci. **PS-15**, 145 (1987).
[10] Donald L. Lee, *Electromagnetic Principles of Integrated Optics* (Wiley, New York, 1986), Chap. 4.